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TOPOLOGICAL STRUCTURE REENGINEERING REGIONAL ELECTRIC POWER SYSTEMS

This paper analyses the topology of a regional power system distribution grid. This research improves the efficiency of the electric power system's operation by using upgrading the redesign (reengineering) methods of topological structures within distribution grids. The ***research object*** *is an electric power system that consists of generation, transmission and distribution parts and requires reengineering. The subject of research is the reengineering of the topology of the power system distribution grid. To achieve the research purpose, modifications of k-means algorithm as well as the small step algorithm based on the statistical analysis, clustering and minimum spanning tree development methods of Prim and Kraskal are used. The modifications described in this paper allow for optimization of the network based on user needs, properties of the operating grid elements, and other additional constraints for flexibility and generality. Given the varying parameters, this method provides the means to redesign parts of the distribution grid, keeping its certain elements safe from displacement, but also the means to redesign the whole distribution grid, including changes to the number and location of transformer substations and transmission lines.* ***Conclusions****. To solve the problem of determining the territorially close groups of consumers in the paper, it was proposed to use the k-means clustering algorithm. This algorithm allows us to divide consumer sets into clusters, so that coordinates of their centres will be recommended as locations of transformer substations. The modernization of the k-means algorithm was proposed by developing procedures for adding and combining clusters using different strategies for determining starting centroids. Based on this, a method for reengineering the topological structures of regional electric power systems in terms of the possibility of their fundamental restructuring was developed. The results of this research may be useful to various enterprises, organizations or institutes dealing with the elaboration or design of electric power system development on the corporate, regional or local level.*

Keywords: *K-means algorithm; electric power system; clustering; reengineering; distribution grid; structure; topology; optimization.*

Introduction

As part of infrastructure, an electric power system (EPS) along with pipelines as well as highway and railway networks is a typical example of a complex territorially dispersed object. It is characterised by long distances and complex structures, including sets of diverse elements: power generating objects (electric power stations), transformer substations that increase or decrease the voltage, high-voltage power lines and transmission lines, etc.

Increased public welfare as well as improved ecological requirements to production, transportation and social facilities also result in altered requirements to EPS. There are new requirements to technologies, generation efficiency and environmental impact, consumption characteristics and geography change as well. EPS are to meet the latest requirements. This in its turn requires modernization and renovation. Unfortunately, at this point, regular equipment renovation does not suffice, what is needed, is EPS reengineering.

EPS reengineering is a complex multi-step process aiming at redesigning the system so that it corresponds to the modern requirements of the society and acquires enhanced functional and economic values [1]. Given a certain way of system organization it is possible to supply the production with stable, cheap and quality electric power, thus decreasing production costs and improving the competitiveness of industry products. Impacts of irrational grid organization include abrupt voltage fluctuations, which cause faster equipment depreciation, its damage and power shortages.

1. State-of the Art and Objectives

Reengineering enables construction of a completely new grid based on the elements of the existing EPS. However, not every modernization brings improvements, effects of some modernizations may only be seen with time or under certain circumstances. In order for the reengineering of such a complex system as an EPS to be successful, it is highly important to conduct a thorough analysis and modelling of both its static characteristics as well as dynamics of it operation processes [2].

The review of scholarly publications shows that within market economy and current state of power supply

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complex development, one of the main problems, which has been addressed by experts over the past ten years, is the reduction of power loses during transportation and consumption. To solve this problem there are efforts to design a new EPS with reduced costs or optimise the existing one. One of the possible solutions is introduction of Smart Grid to the EPS [3, 4].

Scientific research in this area is as a rule implied to solving the tasks on pre-project phases. Project phases require more precision, whereas standardised engineering tools hinder the conduction of purely scientific research. At the same time, large capital investments in the construction and renovation of an EPS have to be based on the comprehensive and informative argumentation of project decisions. Therefore, most of the research effort is dedicated to the development of mathematical models as well as search and argumentation methods for optimal solutions [5-8].

To date there is a wide range of varying methods, algorithms and software to compute, regulate and estimate technical power losses in distribution grids. Despite considerable achievements, the focus remains on further improvement of the already elaborated methods and algorithms likewise development of the new ones on their basis, as well as elaboration of efficient solutions in order to estimate power losses within EPS and power distribution processes.

During the scientific conference titled Information Technology in Disaster Risk Reduction (ITDRR 2019) the application of EPS reengineering in case of natural and other disasters [9] was actively discussed, furthermore, the use of social-economic approach in order to design a new generation of EPS was examined [10].

The object of current research is an EPS, it consists of generating stations, step up transformers, transmission lines, step down transformers, distribution grid and customers (Fig. 1).

Let us look at an EPS distribution grid, consisting of customers, transformer substations (TS) that reduce the voltage and high voltage power lines that connect TS to transmission lines (TL). In order to minimise the total length of transmission lines (thus reducing as much as possible voltage losses in electrical conductors), the location of TS and customer connection channels should be changed. Different countries use varying approaches to calculate voltage losses, however, several important characteristics remain the same:

– the longer the conductor, the higher the losses;

– the higher the consumption capacity, the higher the losses;

– the lower the voltage during the transmission, the higher the losses.

Voltage values during power transmission reach their minimum in the phase of distribution to consumers. Thus, one of the objectives to be set reads as minimisation of the total length of TL that connects transformer substations to final consumers. Still the process of TS and high voltage power lines setup has its own economic costs. EPS reengineering in its turn enables a complete reconstruction of the system, renewal of its technological basis and also ensures the flexibility of the system regarding changes in the consumption topology.

The EPS should be redesigned in such a way that the total length of the distribution grid is reduced to minimum, $L = \sum_{i=1}^{n} l_i \rightarrow \min$ with l_i – as the length of connection between the consumer and transformer substation, n – as the number of such connections. The model of the target function should include losses, emerging from the TS setup, thus the minimisation of the total length of the distribution grid should go along with the minimisation of the number of TS.

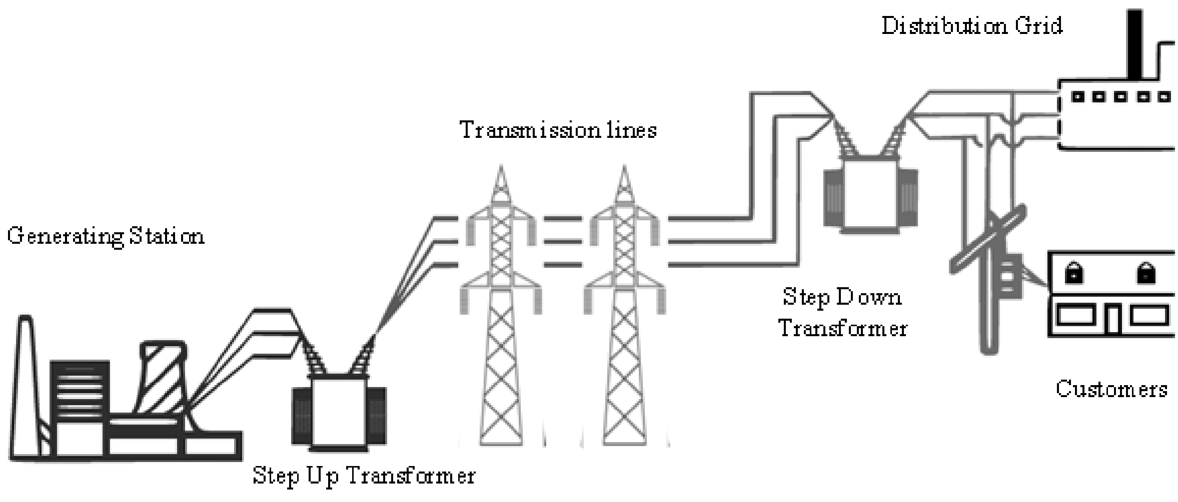

Fig. 1. Electric power system scheme

Furthermore, the task may be reduced to voltage loss minimisation, in which case it reads as follows:

$$\Delta U = \sum_{i=1}^{n} \Delta u_i + \sum_{j=1}^{m} \Delta u_j^{TS} \rightarrow \min, \qquad (1)$$

with ΔU – as total voltage loss;

Δu_i as power loss during the transmission via the i-th cable;

n as the number of consumers;

Δu_j^{TS} as power loss in the j-th TS;

m as the number of TS.

Thereby the following conditions are to be met:

– the length value of any consumer-TS connection has to be smaller than the set value of $\forall l_i \leq l^H$, the value of l_i^H may be both common for all connections and unique, depending on the conductor type, consumption capacity, peak loads and other performance characteristics;

– TS have to be located at a certain distance from consumers, its precise value depends on the characteristics of the TS equipment, safety facilities containing the TS equipment as well as equipment capacity;

– the preference usually goes to the reengineering proposal with the lowest implementation costs. These costs include: costs of making new consumer-TS connections, costs of a new TS placement, costs of connecting a new TS to transmission lines, costs of current consumer-TS connection modernization, costs of current TS modernization, losses during power distribution to consumers

$$C = \sum_{i=1}^{p} c_i \rightarrow \min, \qquad (2)$$

with C as total costs;

c_i as one cost item;

p as the number of such items.

Solving this task does not require immediate decisions allowing therefore further requirements examination and improving the precision of modelling.

One has to understand that it is rather difficult to estimate the costs, it is even more difficult to present the total costs as a clear mathematical relation. One of the possible approaches to estimate the costs determines the difference between the amount of output power at the electric power station and the input power reaching the consumers. This approach may incorporate not only technical, but also commercial costs, possibly misrepresenting the situation and causing modelling inaccuracy. Besides such costs are as a rule identified in the operational rather than planning phase.

An alternative approach considers a solely physical component of costs. There is a functioning mathematical and physical model to calculate possible losses. Estimation of line (between the phases) voltage loss in the cable with the three-phase alternating current may be calculated using the following correlations [11]:

$$\Delta U(V) = \frac{P \cdot R \cdot I + Q \cdot X \cdot l}{U_{line}}, \qquad (3)$$

$$\Delta U(\%) = \frac{P \cdot R \cdot I + Q \cdot X \cdot l}{U_{line}^2}, \qquad (4)$$

with $\Delta U(V)$ as voltage loss in volts;

$\Delta U(\%)$ as voltage loss in percentage;

P as active power transmitted in the line, W;

V as voltage, V;

I as amperage, A;

Q as reactive power transmitted in the line, var;

R as electrical resistance of the cable, Ω / m;

X as inductive reactance of the cable, Ω / m;

l as length of the cable, m;

U_{line} as line voltage of the grid, V.

Otherwise, if we know the current:

$$P = \sqrt{3} \cdot I \cdot U_{line} \cdot \cos\varphi, \; Q = \sqrt{3} \cdot I \cdot U_{line} \cdot \sin\varphi,$$

with φ as angle between the voltage and current vectors of the corresponding phase.

the abovementioned formulas (3) and (4) read:

$$\Delta U(V) = \sqrt{3} \cdot I \cdot (R \cdot \cos\varphi \cdot l + X \cdot \sin\varphi \cdot l),$$

$$\Delta U(\%) = \frac{\sqrt{3} \cdot I \cdot (R \cdot \cos\varphi \cdot l + X \cdot \sin\varphi \cdot l)}{U_{line}}.$$

Estimation of phase (between the phase and neutral wire) voltage loss in the cable is calculated using the formulas (5) and (6):

$$\Delta U(V) = \frac{2 \cdot (P \cdot R \cdot I + Q \cdot X \cdot l)}{U_{phase}}, \qquad (5)$$

$$\Delta U(\%) = \frac{2 \cdot (P \cdot R \cdot I + Q \cdot X \cdot l)}{U_{phase}^2}, \qquad (6)$$

with U_{phase} as phase voltage of the grid, V.

Otherwise, if we know the current:

$$P = I \cdot U_{phase} \cdot \cos\varphi, \; Q = I \cdot U_{phase} \cdot \sin\varphi,$$

the abovementioned formulas (5) and (6) read:

$$\Delta U(V) = 2 \cdot I \cdot (R \cdot \cos\varphi \cdot l + X \cdot \sin\varphi \cdot l),$$

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$$\Delta U(\%) = \frac{2 \cdot I \cdot (R \cdot \cos\varphi \cdot l + X \cdot \sin\varphi \cdot l)}{U_{phase}}.$$

Yet an approach, which is based on the analysis of physical processes only, cannot incorporate all operating conditions or additional costs, which may emerge due to unstable grids. Voltage fluctuations affect adversely not only TS equipment, but also consumers' industrial and household appliances. Furthermore, commercial costs are in this case left out. This explains the relevance of applied scientific problem setting for the reengineering of topological structures of regional electric power stations.

The model of the Steiner tree problem may be used for the distribution grids optimization (reengineering) [12]. It is a generalisation of the classical Steiner problem, similar methods, particularly evolutionary algorithms are used to solve it.

General methods of distribution grids optimization include: coordinate descent optimization method, genetic algorithm synthesis, tabu search, branch and bound algorithm, and k-means clustering [13]. Most of the above-mentioned methods enable construction of an optimal distribution network structure, but they raise certain restrictions when applied to the reconstruction of an existing EPS, requiring thus their modification. For instance, a vast majority of these methods require definition of the set of possible node placements (TS), which is a rather difficult task given the scope of the grid, placement of the nodes on the basis of existing elements is also not possible due to the structural attributes of an EPS. Another problem is a limited connection distance between consumers and TS, which has to be taken into account when connecting the node. Consequently, the number of nodes may not suffice leaving some of the elements disconnected, or it may overpass resulting in finding a suboptimal decision. Therefore, it was decided to modify the k-means clustering method to conform the EPS specifications.

In order to improve the operational efficiency of regional power grids by means of advancing the method of their topological structure reengineering, it is necessary:

– to analyse the existing clustering algorithms and decide on the one enabling prompt and correct partition of the customer set into transformer substations' service areas;

– to improve the customer clustering algorithm on the basis of 'precision-complexity' composite index applied to the task of the EPS distribution grid optimization;

– to improve the solution method of regional power system topological structures reengineering in such a way that it includes the possibility of their fundamental reconstruction;

– to develop algorithms and software to optimise the project of regional power system topological structures reengineering;

– to conduct experimental research in order to determine the efficiency of the proposed method and algorithms.

2. Methods and Tools

The EPS distribution grid examined in this paper has a tree-like structure. It consists of a set of centres (step down TS connected to a high-voltage power line), with sets of consumers linked to each of the centres. EPS distribution grid reengineering method, which is developed in this paper, will be built upon the improved algorithm of k-means territorial clustering of consumers. The starting placement of centroids may be determined using the following algorithms:

– multistart (random placement of centroids);

– use of existing TS coordinates;

– minimum spanning tree;

– Small Step (clustering algorithm based on gradual integration of clusters and reduction of their number).

K-means algorithm has a number of modifications, most of them relate to the addition rule of a new element to the cluster and re-computation of its centre. Advantages of this algorithm include: relatively high efficiency with simple realisation; high quality of clustering; possibility of parallel implementation and available modifications.

Deficiencies of this algorithm list: the number of clusters is one of the algorithm's parameters; sensitivity to the initial conditions – initialisation of cluster centres affects considerably the results of clustering; sensitivity to outliers and noises – outliers that are far from the clusters' centres are similarly taken into account when computing their centres; the possibility of convergence towards local optima – an iterative approach does not guarantee convergence towards optimal solution.

Initial set in the method implementation process shall be the set of consumer coordinates $S = \{s_i\}$, $i = \overline{1, n}$, with n as the number of elements within the consumer set. The set S has to be parted into subsets – clusters $K = \{k_j\}$, $j = \overline{1, m}$, m as the number of clusters that the consumer set is parted into, each of the cluster shall be maintained by one TS.

Conditions of parting a set into subsets – clusters:

– partition takes place in such a way that every element of the consumer set is included into one of the clusters;

– every element of the consumer subset may be included into one cluster only, i.e. cluster subset intersection has to be empty, $k_i \cap k_j = \emptyset$, with $i \neq j$; $i, j = \overline{1, m}$;

– every cluster has to include at least one element, i.e. a cluster cannot be empty, $k_i \neq \emptyset; i = \overline{1, m}$.

Several additional parameters have to be determined for every customer: maximum permissible length of connection conductor; estimated scope of power consumption; statistical data on peak loads. Moreover, initial data should also include information on the distribution grid that is already in operation or will be used for redesign (reengineering).

The verification procedure of possibly including an element into a cluster implies: computing the distance to the centroid and adding the element to the cluster if this distance is shorter than the maximum length of connection conductor. Otherwise, the element is left out. The algorithm stops when following the iterative repetition all elements are included into the same clusters. Given the characteristics of the task, in the process of operation there might be situations when certain clusters have no elements or certain elements are not included in any of the clusters. Sometimes both of these situations happen simultaneously (Fig. 2, a).

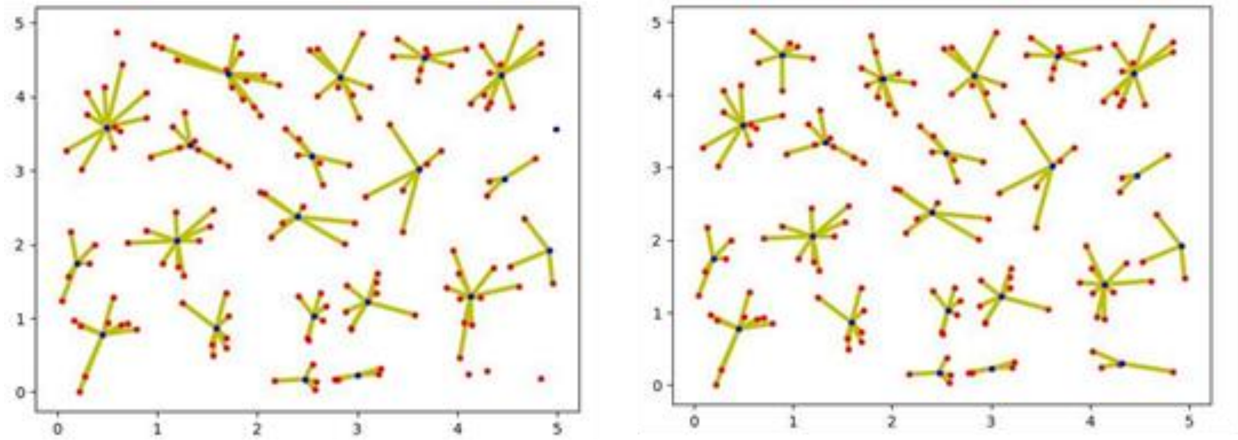
If there are empty clusters left, they are considered redundant and excluded from the process, thus the number of TS decreases. If there are free elements (customers) left, additional centroids of new clusters are placed accordingly and the algorithm restarts (Fig. 2, b).

Should the k-means algorithm part all the elements into clusters at the first attempt with no added clusters, the procedure of their reduction launches next. This procedure attempts to reduce the number of clusters by means of excluding the centroids that are located next to one another. Having identified such centroids, the algorithm exchanges them to a new one located in the middle of them. This procedure of cluster reduction repeats until at least one of the elements is included into one of the clusters. The final version of topology is considered the last successful partition.

K-means algorithm is sensitive to the setting of initial centroids, their number and location. It is worth mentioning that some of the centroids may have fixed coordinates (it has to do with the characteristics of the EPS). In this case the load centre of such a cluster does not shift, which was also integrated into the algorithm modernization.

Let us examine the functioning of the algorithm given varying placement algorithms of the initial centroids.

Figure 3, a presents the initial data. Figure 3, b shows algorithm results using random setting of the initial centroids and Figure 3, c shows algorithm results using the coordinates of the existing TS. At the beginning 40 initial centroids were placed. Having conducted the clustering, the algorithm automatically increased or decreased the number of clusters in order to meet one of the given conditions – all elements had to be included into one of the clusters. As can be seen, the results of this clustering considerably differ in both the number of clusters and their location and content.



a) b)

Fig. 2. Comparison of classical k-means (a) algorithm
and its modifications with connection length restriction (b)

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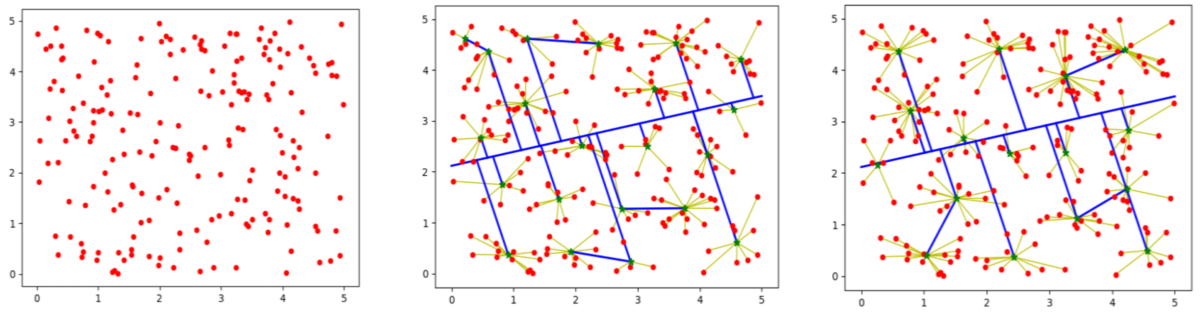


a) b) c)

Fig. 3. Comparison of classical k-means (a) algorithm and its modifications with connection length restriction (b, c)

In terms of clustering both results are ‘successful’, namely there are no empty clusters left, there are no free elements, all clusters are formed correctly and the restrictions of maximum conductor length are also met. However, in terms of target function that takes into account the total length of the distribution grid, the number of TS and the length of connecting lines up to the transmission line, these two results are completely different.

A distinctive feature of the EPS reengineering task is having an existing system in place with its consumers and TS, it may be inefficient or partially ruined (e.g. as a result of natural disasters [9]), but coordinates of its TS may be used to place the initial centroids. Advantages of this strategy of setting initial centroids list: simplicity of its realisation; no need of additional information; no need of using additional algorithms or methods.

Deficiencies of this strategy include: excessive binding to the existing EPS, which may lead to distortion of clustering results and consequently missing out on more efficient solutions; an EPS requiring reengineering obviously has defects in its structure (otherwise there is no need of modernization), therefore using the same design solutions may lead to preservation of these defects or their amplification.

One of the easiest ways to start an algorithm is to use random setting of centroid coordinates. Given a large number of attempts, the results may be satisfactory. This happens because centroids shift, ensuring thus their equal distribution within the clustering area. However, continuous space and large numbers of clusters result in an excessive number of runs that the algorithm with random centroid setting has to carry out. Still even in such a case the suggested modification of the k-means algorithm enables a cluster partition that would meet the requirements. However, results of this partition may sometimes turn out unacceptable: extra clusters are added; concentration of clusters in one area might be too high; or there may be empty clusters left.

Benefits list:

– ease of implementation;

– no binding to the output grid, which should ensure higher efficiency of the elaborated solution.

Disadvantages include:

– difficulties in estimating algorithm’s complexity due to unpredictable results;

– the algorithm may present incorrect solutions, which may become a problem given a small number of restarts;

– a large number of restarts requires additional time to find the solution.

It is also possible to use an algorithm based on the minimum spanning tree creation in order to determine the initial centroids.

General description of the algorithm.

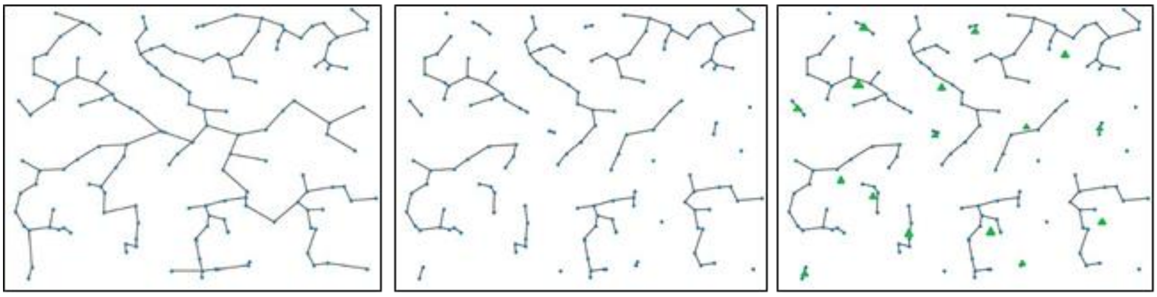
Step 1 – bringing a set of objects into a graph. Elements of consumer set shall be the vertices of the graph and distances between the vertices shall be the weights of the edges.

Step 2 – creating a minimum spanning tree. We shall use Prim’s and Kruskal’s algorithm (Fig. 4, a).

Step 3 – clustering by means of gradual edge elimination. If we know the number of clusters k, the k-1 edge with the largest length will be eliminated, as a result we have k connected components – clusters. When solving a task with the unknown total number of clusters, it is recommended to eliminate the edges whose length is larger than a certain threshold value. In our case we shall use the average length of all edges. In other words, if a graph’s edge is longer, it will be eliminated. If every element has its own restriction, the edge that is longer than the sum of the restrictions set for all elements forming this edge, will be eliminated. Results of edge elimination are shown on Figure 4, b. If following the edge elimination it is still not possible to make a rational placement of the initial centroids, further longest edges should be removed until the number of clusters is acceptable.

Step 4 – defining the centroids of the resulting clusters (Fig. 4, c).

Step 5 – starting the k-means algorithm to complete the clustering.



a) b) c)

Fig. 4. The process of algorithm functioning to determine the initial centroids using minimum spanning tree creation (Prim's and Kruskal's algorithm) a) creation of a minimum spanning tree, b) elimination of edges failing to meet the condition, c) definition of centres

The elaborated Small Step algorithm may be used for independent cluster definition, however, it is less efficient than k-means algorithm and fails to meet all the requirements set by the given task.

The essence of this algorithm may be described as follows.

Step 1 – defining the set of all elements to undergo clustering (Fig. 5, a).

Step 2 – determining the minimal distance between any two elements.

Step 3 – algorithm stop check. The algorithm pauses and shifts to Step 5 if all elements are distributed and there are no allowed connections left or if the minimum distance between the vertices is larger than the restriction of the maximum conductor length.

Step 4 – checking the conditions:

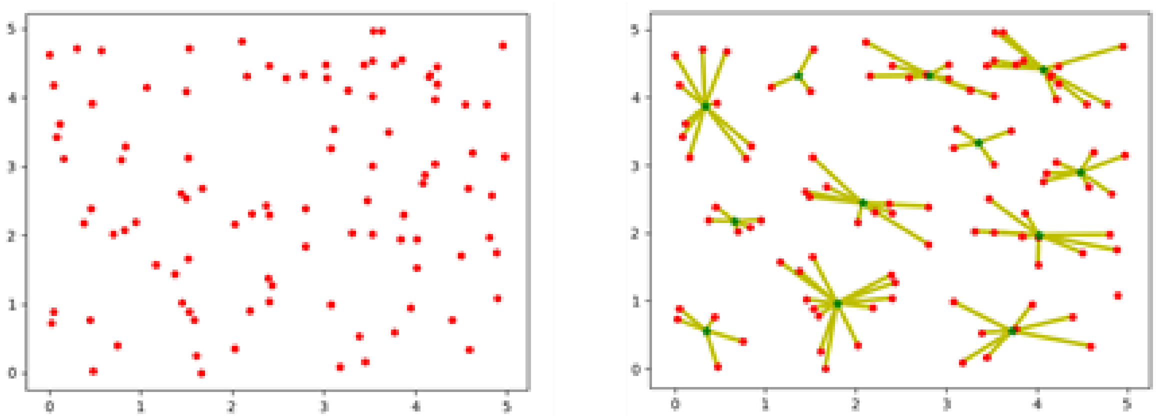
– if neither of the elements is included into a cluster, a new cluster is created and both elements are added to it;

– if one of the elements was previously included into one of the clusters, it is checked whether this element can be added to the cluster. That is, it is checked if the distance from this element to the other ones included into the cluster is shorter than the double restriction of the conductor length. Should this check be successful, the element is included into the cluster, otherwise it is prohibited to consider the connection of these two vertices. Return to Step 2;

– if both elements were previously included into clusters, it is checked whether these clusters can be united. For this, the remoteness of every element in one cluster from every element in the other one is checked. Should this check be successful, the clusters are united, otherwise it is prohibited to consider the connection of these two vertices. Return to Step 2.

Step 5 – computing of cluster centroids as load centres (results presented on Fig. 5, b).

This algorithm estimates the number of clusters required and calculates an approximate location of centroids, thus it accelerates k-means algorithm and contributes to a higher efficiency of the topology.



a) b)

Fig. 5. The process of algorithm functioning to determine the initial centroids using Small Step algorithm: a) a set of points (consumers), b) defining the centroids

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3. EPS Reengineering Method

The algorithms of setting the initial centroids described above enable modifications of an existing k-means algorithm implementation and formulation of methods to solve EPS distribution grid reengineering.

The method suggested below implies realisation of a set of phases.

Phase 1 – finding a new EPS topology. In the process of clustering, k-means algorithm elaborates a new EPS distribution grid topology. Normally the algorithm generates several topology versions. This has to do with both multistart and implementation of varying strategies to choose the initial centroids. Depending on the chosen clustering strategy, some of the topology versions may result rather costly. Cluster and their centroids formation is only an intermediate phase. Having elaborated an efficient topology, it is necessary to compare it to the existing EPS topology and estimate the costs.

Phase 2 – comparing elaborated and existing topologies. For this it is necessary to examine centroids that would be set using recommended TS placement coordinates as well as those that would be set using existing TS coordinates. The purpose of this comparison is to determine whether it is feasible to use the existing TS in order to decrease the modernization costs of the distribution grid. Reduction of costs may be possible due to high probability of already existing transmission line connection channels, support facilities as well as consumer connection channels, meaning there is no need to build the new ones. Should the elaborated and the existing TS be next to each other, it is necessary to check the possibility of a centroid shift. For this the remoteness of cluster elements to the new centroid has to be computed. If the check of all elements is successful, it is decided to use the existing TS.

If at least one of the elements fails the check, the option becomes to shift the centroid according to the additional modelling – the centroid is then fixed and the clustering algorithm is restarted, new topology versions are analysed to choose the most efficient one regarding the target function. Should the existing TS be meant to be used, it becomes subject of check for the necessity of its modification. The required consumption capacity and peak loads are computed and compared to the characteristics of the existing TS.

Phase 3 – estimating the costs of reengineering project. Total cost of the project is the main assessment factor of various topology versions and consequently reengineering measures. Total cost includes the following:

– cost of new TS placement $\left(C_{TS} = c_{TS} \cdot N_{TS}\right)$, with c_{TS} – as the cost of new TS placement, N_{TS} – as the number of new TS, if every TS has varying placement costs, which is logical given the scope of the territorially distributed grid, then $C_{TS} = \sum_{i=1}^{N_{TП}} c_{TSi}$;

– cost of connection to the transmission line $\left(C_{CTS} = c_{CTS} \cdot \sum_{i=1}^{N_{TS}} l_i^m\right)$, with c_{CTS} – as the cost of laying 1 km of communications, l_i^m – as the length of connection cable to the transmission line in km. As a rule cost of cable laying remains the same;

– cost of TS modernization $\left(C_{MTS} = c_{MTS} \cdot N_{MTS}\right)$, with c_{MTS} – as the cost of TS modernization, N_{MTS} – as the number of TS requiring modernization, if every TS has varying modernization costs, then $C_{MTS} = \sum_{i=1}^{N_{TS}} c_{MTSi}$;

– cost of laying distribution grid channels from TS to consumers $\left(C_K = c_K \cdot \sum_{j=1}^{N_K} l_i\right)$, with c_K – as the cost of laying 1 km of communications, l_j – as the length of connection cable in km, N_K – at the number of consumers requiring the connection.

Total cost including all the above mentioned elements reads:

$$C = C_{TS} + C_{CTS} + C_{MTS} + C_K. \quad (7)$$

Figure 6, a, and Figure 6, b presents examples of distribution grid topologies with varying cost estimations given the random choice and minimum spanning tree strategies correspondingly.

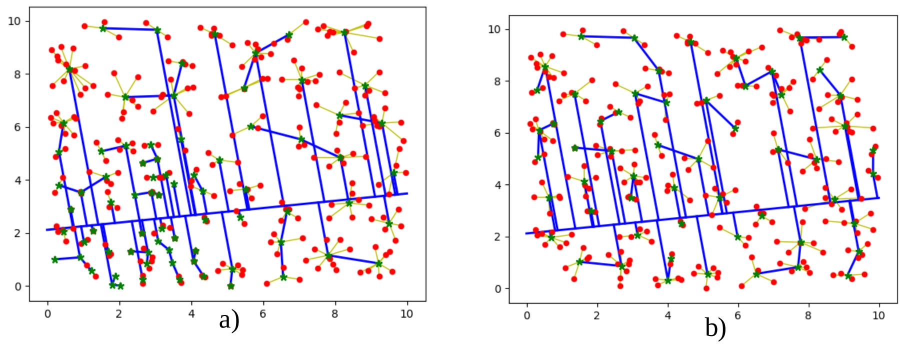

Fig. 6. Examples of distribution grid topologies: a) topology example with the estimated cost C = 943201.31 USD, b) topology example with the estimated cost C = 722356.66 USD

4. Results and Discussion

Method improvements and elaborated algorithms described in this paper were implemented in software. Using this software a series of experiments were conducted to analyse the indicators of precision and time complexity. In the experiments we solved the tasks incorporating 100, 150, 200, 250 and 300 customers. Using a random number generator we set the coordinates of customers placement and coordinates of existing TS. Estimations of time spent on solving the tasks and costs of various EPS distribution network construction options were made on the basis of 20 experiments. In order to conduct an experiment, it is necessary to set the initial data on the original EPS. This data includes:

– customer coordinates – are usually considered the entrance point or distribution box of a residential house or the distribution module of a production facility. It is more correct to indicate the connection point of a household appliance or production equipment, but computing shows that the distance between the entry point and the remotest customer rarely exceed 100 m and voltage drop remains within permissible fluctuation limits;

– consumption characteristics. It is not uncommon for the number of consumption parameters and customers to reach several dozens. Within the framework of current research their number is reduced to two: capacity and peak loads. This restriction will not affect the efficiency estimation of the suggested EPS distribution grid optimization method. The two chosen parameters of capacity and peak loads will provide the data necessary to answer the question of TS modernization feasibility;

– TS coordinates. TS placement goes along with the construction of additional protective and infrastructure facilities. Depending on the consumption capacity, it either requires a separate building or is attached to the transmission tower. This information is relevant for the system reengineering, it is required to compare estimated and existing coordinates of a TS;

– customer connection lines – this information is relevant for the reengineering and is used to estimate the costs of reengineering scenarios;

– connection of a TS to the transmission line – same as in the abovementioned paragraph, this information is used to estimate the TS connection costs and consequently it helps to make more precise cost estimations and choose a more efficient solution.

The main modelling results are presented in Table 1. The sets of 100, 150, 200, 250 and 300 customers were used for the modelling.

Table 1

Summarised indicators of phase modelling of EPS distribution grid reengineering derived from 20 software runs

№	Strategy	Strategy operating time, sec	K-means operating time, sec	Total operating time, sec	Cost of reengineering, USD
EPS distribution grid with 100 customers					
1	Coordinates of existing TS	0.001	0.84	0.841	16522.5
2	Random choice	0.004	0.599	0.603	20876.2
3	Minimum spanning tree	0.138	0.42	0.558	26279.0
4	Small Step	11.83	0.116	11.95	16781.8
EPS distribution grid with 150 customers					
1	Coordinates of existing TS	0.0045	1.23	1.2345	20762.1
2	Random choice	0.0045	2.94	2.9415	20385.5
3	Minimum spanning tree	0.25	2.75	3	18650.6
4	Small Step	58.18	0.6	58.78	18492.3
EPS distribution grid with 200 customers					
1	Coordinates of existing TS	0.0016	5.5	5.50	20057.3
2	Random choice	0.005	4	4.005	23799.2
3	Minimum spanning tree	0.4	4.8	5.2	22242.8
4	Small Step	177.4	1.2	178.6	21348.5
EPS distribution grid with 250 customers					
1	Coordinates of existing TS	0.0017	7.6	7.601	75261.3
2	Random choice	0.006	7.75	7.76	86936.5
3	Minimum spanning tree	0.54	7.25	7.79	71832.9
4	Small Step	300.5	1.5	302	58508.1
EPS distribution grid with 300 customers					
1	Coordinates of existing TS	0.0018	11.44	11.4418	66461.6
2	Random choice	0.0063	11.95	11.9563	86259.3
3	Minimum spanning tree	0.64	11	11.64	69507.5
4	Small Step	411.76	1.73	413.49	58509.8

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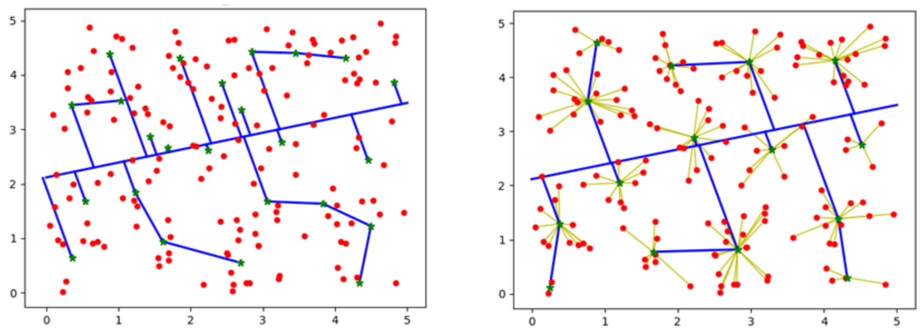

a) b)

Fig. 7. Example EPS distribution grid: a) existing EPS distribution grid, b) results of EPS distribution grid reengineering

Estimations of the costs of reengineering scenarios were made on the basis of (7) model. $c_{ТП}$ (cost of TS placement) constitute 10000 USD per item, $c_{ПТП}$ (cost of laying 1 km of communications) – 500 USD, $c_{МТП}$ (cost of TS modernization) – 1000 USD, $c_{К}$ (cost of laying 1 km of communications) – 100 USD. These values result from the comparison of estimated costs of various construction projects with similar objects.

Figure 7, a shows initial EPS topology, Figure 7, b presents results of reengineering.

When analysing the data, it is not recommended to prioritise one certain combination. In practice the operating time of engineering or reengineering algorithms is not limited to minutes or hours of functioning. However, it increases considerably with the increase of the number of grid consumers. Even the fact that k-means algorithm may be implemented using parallel computing technologies, cannot compensate an increase of time required for modelling given a large number of customers.

Operating time required for the 'Coordinates of existing TS' strategy is relatively short, as it does not determine the coordinates of new centroids. Yet it requires formation of the necessary data sets in order to continue the run.

When implementing the 'Random choice' strategy, the algorithm spends time only on the generation of random values that constitute 20 % of the total number of customer set. This time does not exceed 1 second.

When using the 'Minimum spanning tree' strategy, the operating time increases linearly. The use of time nearly coincides with the computing complexity of Prim's and Kruskal's algorithm applied to create the tree.

Algorithm operating time required for the 'Small Step' strategy increases almost linearly. It is worth mentioning that the operating time of 'Small Step' strategy exceeds any other strategy and grows at a higher rate.

Figure 8 presents k-means algorithm operating times depending on the use of strategies.

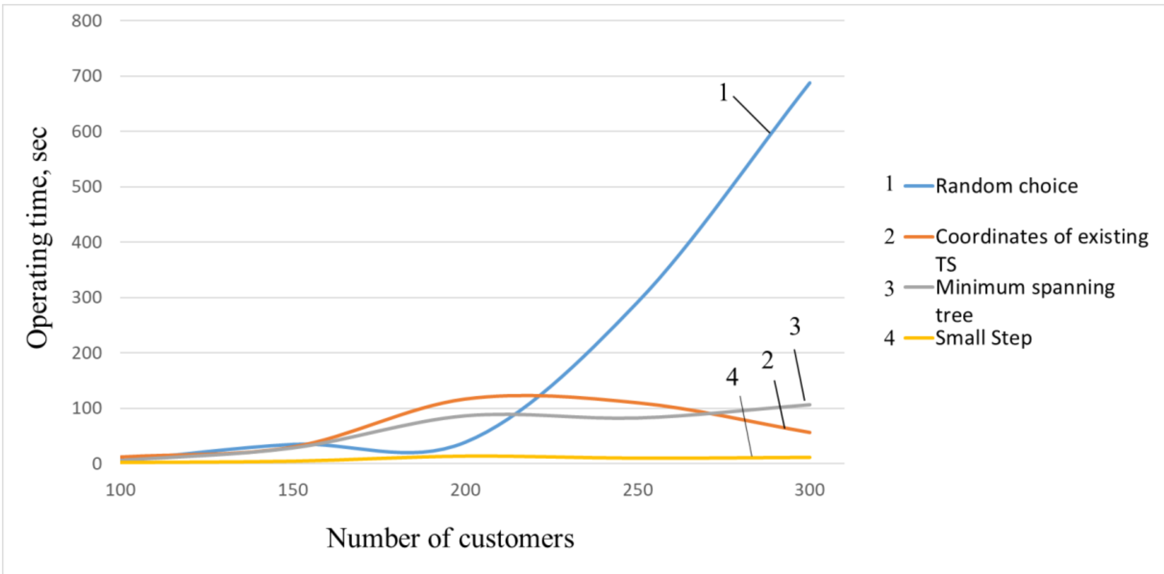

Fig. 8. Operating time of k-means algorithm using varying strategies

Operating time of k-means algorithm differs according to strategies:

– 'Random choice', 'Minimum spanning tree' and 'Coordinates of existing TS' strategies require nearly the same amount of time given the increase of the number of customers;

– 'Small Step' strategy has short operating time, which grows at a slow rate with the increase of the scope of the task;

– 'Coordinates of existing TS' strategy may have varying operating times, following only the time required by the 'Small Step' strategy. This may be explained by the fact that the existing grid is well-designed and only few changes in consumer topology took place during the operating period;

– 'Minimum spanning tree' strategy requires operating time that increases slowly with a linear trajectory.

Results of experimental research (Fig. 9) show that the 'Small Step' strategy generates most economic options, whereas the 'Random choice' strategy almost always generates the costliest ones. 'Small Step' strategy is capable of generating most attractive results, but the amount of time it requires to determine the centroids rapidly increases depending on the consumer numbers.

Conclusions

Regional electric power systems belong to the category of territorially distributed large scale systems. Reengineering of this type of objects implies solving a set of combinatorial tasks of structural, topological, parametric and technological optimization [13]. Most of combinatorial tasks of EPS optimization have no efficient solutions.

Results of the problem analysis of EPS design and operation indicate that most power losses take place during power distribution within the grid. Losses may be reduced by means of distribution grids modernization and implementation of one of the following concepts: MicroGrid, Resilient Grid, Strong Grid and Smart Grid. Their implementation requires reconstruction of the existing EPS using reengineering strategy based on the estimations of power consumption geography development. It is proposed to apply the dynamic time warping (DTW) algorithm in order to analyse the dynamics of power consumption. Comparison of consumption dynamics within a day, week, season and etc. will enable more precise modelling and consumption estimations.

It is proposed in the paper to use the k-means clustering algorithm in order to solve the task of defining territorially close groups of consumers. This algorithm enables consumer set partition into clusters, coordinates of these clusters' centres are then recommended to be set as coordinates of transformer substation placements. The paper proposes k-means algorithm modernization by means of adding and uniting the clusters with varying strategies of determining their initial centroids. This is then used a basis for further development of reengineering method of regional EPS topological structures including the possibility of their fundamental reconstruction.

The proposed method and algorithms were incorporated in software. The results of experimental research determined the indicators of their precision and time complexity. Cost savings within the taken test cases reached 14.2 % due to distribution grid reengineering based on the proposed method. The proposed approach to the EPS reengineering may be utilised by public utility services or large private enterprises in order to modernise the grids of varying hierarchical levels.

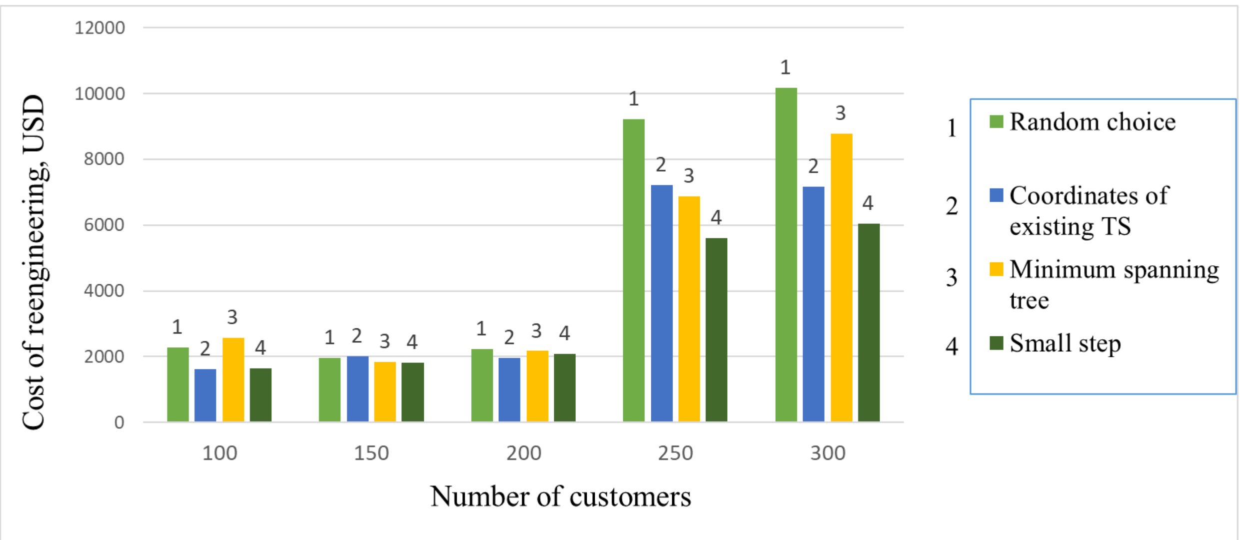

Fig. 9. Cost of reengineering given varying number of customers

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Author Contributions: formulation of the purpose and tasks of research and described the methods of multistart (random placement of centroids) and minimum spanning tree and formulation of conclusions, this corresponds to part of section 3. Methods and Tools and Conclusion – **Alina Nechiporenko;** formulation the introduction, review and analysis of references, this corresponds to the sections Introduction, 1. Literature Review – **Yevhen Hubarenko;** modernization of K-means method, development of "Small step" method, UES reengineering method, implemented software and analysed results of methods, this corresponds to part of section 3. Methods and Tools, section 4. EPS Reengineering Method, 5. Results and Discussion – **Maryna Hubarenko**.

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РЕІНЖИНІРИНГ ТОПОЛОГІЧНОЇ СТРУКТУРИ РЕГІОНАЛЬНИХ ЕЛЕКТРОЕНЕРГЕТИЧНИХ СИСТЕМ

А. С. Нечипоренко, Є. В. Губаренко, М. С. Губаренко

У цій роботі аналізується топологія розподільної мережі регіональної енергосистеми. **Метою** досліджень є підвищення ефективності функціонування електроенергетичної системи шляхом удосконалення методів перепроектування (реінжинірингу) топологічних структур у розподільних мережах. **Об'єктом досліджень** є електроенергетична система, яка складається з генеруючої, магістральної та розподільної частин, та потребує проведення реінжинірингу. **Предметом досліджень** є реінжиніринг топології розподільної мережі електроенергетичної системи. Для досягнення мети дослідження використовуються модифікації алгоритму k-середніх, а також алгоритму малого кроку, які побудовані на методах статистичного аналізу, кластеризації та розробки мінімального остовного дерева Пріма та Краскала. Модифікації, описані в цій статті, дозволяють оптимізувати мережу, виходячи з потреб споживачів, характеристик елементів сітки, які вже працюють, а також інших додаткових обмежень, що забезпечують гнучкість та універсальність. Враховуючи різні параметри, цей метод забезпечує засоби для перепроектування частин розподільної мережі, зберігаючи певні елементи в безпеці від зміщення, а також засоби для перепроектування всієї розподільної мережі, включаючи зміну кількості та розташування трансформаторних підстанцій і ліній електропередачі. **Висновки**. Для вирішення завдання визначення територіально близьких груп споживачів в роботі було запропоновано використати алгоритм кластеризації k-means, який дозволяє розбити множину споживачів на кластери, координати центрів яких будуть рекомендовані як місця розміщення трансформаторних підстанцій. Була запропонована модернізація алгоритму k-means шляхом розробки процедур додавання та об'єднання кластерів з використанням різних стратегій визначення стартових центроїдів. На її основі дістав подальший розвиток метод реінжинірингу топологічних структур регіональних ЕСС в частині врахування можливості їх фундаментальної перебудови. Результати досліджень можуть бути корисними різним підприємствам, організаціям чи інститутам, які займаються розробкою або проектуванням електроенергетичної системи на корпоративному, регіональному чи місцевому рівні.

Ключові слова: алгоритм K-середніх; електроенергетична система; кластеризація; реінжиніринг; розподільна мережа; структура; топологія; оптимізація.

РЕИНЖИНИРИНГ ТОПОЛОГИЧЕСКОЙ СТРУКТУРЫ РЕГИОНАЛЬНЫХ ЭЛЕКТРОЭНЕРГЕТИЧЕСКИХ СИСТЕМ

А. С. Нечипоренко, Е. В. Губаренко, М. С. Губаренко

В данной работе анализируется топология распределительной сети региональной энергосистемы. **Целью** исследований является повышение эффективности функционирования электроэнергетической системы путем усовершенствования методов перепроектирования (реинжиниринга) топологических структур в распределительных сетях. **Объектом исследований** является электроэнергетическая система, которая состоит из генерирующей, магистральной и распределительной частей и требует проведения реинжиниринга. **Предметом исследований** является реинжиниринг топологии распределительной сети электроэнергетической системы. Для достижения цели исследования используются модификации алгоритма k-средних, а также алгоритма малого шага, построенные на методах статистического анализа, кластеризации и разработки минимального

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остовного дерева Прима и Краскала. Модификации, описанные в этой статье, позволяют оптимизировать сеть, исходя из потребностей потребителей, характеристик уже работающих элементов сетки, а также других дополнительных ограничений, обеспечивающих гибкость и универсальность. Учитывая различные параметры, этот метод обеспечивает средства перепроектирования частей распределительной сети, сохраняя определенные элементы в безопасности от смещения, а также средства перепроектирования всей распределительной сети, включая изменение количества и расположения трансформаторных подстанций и линий электропередачи. **Выводы**. Для решения задачи определения территориально близких групп потребителей в работе было предложено использовать алгоритм кластеризации k-means, который позволяет разбить множество потребителей на кластеры, координаты центров которых будут рекомендованы как места размещения трансформаторных подстанций. Была предложена модернизация алгоритма k-means путем разработки процедур сложения и объединения кластеров с использованием различных стратегий определения стартовых центроидов. На ее основе получил дальнейшее развитие метод реинжиниринга топологических структур региональных ЭСС в части учета возможности их фундаментальной перестройки. Результаты исследований могут быть полезны предприятиям, организациям или институтам, которые занимаются разработкой или проектированием развития электроэнергетической системы на корпоративном, региональном или местном уровне.

Ключевые слова: алгоритм K-средних; электроэнергетическая система; кластеризация; реинжиниринг; разделительная сеть; структура; топология; оптимизация.

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